Utilization of HDPE Granules and E-Waste as Aggregate Substitutes in Concrete: A Feasibility and Strength Evaluation Study

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ABSTRACT

This study evaluates the feasibility and performance of using HDPE granules and e-waste as partial replacements for fine and coarse aggregates in concrete. Results indicate that incorporating 12.5% HDPE and 12% e-waste yields a 28-day compressive strength of 26.7 N/mm², satisfying the IS 456:2000 criteria for M25-grade concrete. However, further increases in replacement ratios lead to diminished strength. Slump test results demonstrate reduced workability with higher replacement levels due to the hydrophobic and angular nature of the substitutes. Notably, split tensile and flexural strengths improved, with tensile strength reaching 3.99 N/mm² and flexural strength peaking at 6.8 N/mm². These findings support the potential use of such mixes in non-structural concrete applications like pavements and cycle tracks, where moderate strength and enhanced ductility are desirable.

Key Words: *HDPE Granules, E-Waste Concrete, Sustainable Aggregate Replacement.*

1. INTRODUCTION

Traditionally, the disposal methods for E-waste include landfilling and incineration, both of which pose significant environmental risks due to the release of hazardous substances. However, recent studies have explored the potential of converting E-waste plastics into synthetic aggregates for use in concrete. Specifically, substitutions ranging from 10% to 50% of natural coarse aggregate (NCA) with PCA have shown improvements in properties such as abrasion resistance and reduced captivity coefficients, although mechanical strengths experienced reductions proportional to the replacement levels. Similarly, HDPE, a thermoplastic polymer commonly found in packaging materials, offers potential as an alternative aggregate in asphalt mixtures. Laboratory studies have investigated the dry addition of recycled HDPE into asphalt mixtures, revealing that HDPE can effectively melt during typical production processes, thereby integrating into the asphalt matrix. This integration can potentially enhance the performance characteristics of the pavement, such as increased resistance to deformation and improved durability.

E-Waste: Challenges and Solutions

This poses serious risks to human health and ecosystems. Recycling and repurposing E-waste through proper collection, dismantling, and material recovery can reduce environmental pollution and conserve natural resources. Innovative applications, such as using E-waste plastics in pavement construction, provide sustainable solutions by repurposing non-biodegradable materials into useful infrastructure. Governments and environmental organizations worldwide advocate for E-waste management policies, promoting safe disposal, recycling, and extended producer responsibility (EPR). Public awareness and responsible consumer behaviour, such as donating or recycling old electronics, can further alleviate the bad influences of E-waste, ensuring a more maintainable and round economy.

HDPE Granules: Properties and Applications

High-Density Polyethylene (HDPE) granules are small, pellet-like plastic particles derived from virgin or recycled HDPE materials. These granules serve as the raw material for manufacturing various plastic products, including pipes, containers, packaging materials, and construction components. HDPE granules exhibit excellent mechanical properties, such as impact resistance, flexibility, and low moisture absorption, making them ideal for infrastructure applications like pavement construction. In road engineering, HDPE granules can be blended with asphalt or concrete, enhancing rutting resistance, durability, and water repellence. Their non-biodegradable nature makes them suitable for long-lasting applications, minimizing material degradation over time. However, challenges like workability issues and high-temperature softening must be addressed through optimized mix designs and additives. With increasing emphasis on eco-friendly construction practices, HDPE granules are gaining popularity in pavement engineering, contributing to sustainable and resilient infrastructure development while promoting circular economy principles.

2. MATERIALS AND METHODOLOGY

This chapter elaborates on the materials utilized, the procedures followed for the mix design, and the experimental methodology adopted to study the influence of using HDPE granules and e-waste as incomplete replacements for fine and coarse totals, respectively, in M25 grade real. The aim was to evaluate the feasibility of incorporating these waste materials in concrete applications, particularly in pavement construction, without compromising on strength and durability. All design and testing procedures were carried out in agreement with pertinent Indian Values to ensure the dependability of results.

Materials

The materials selected for the experimental program were chosen for their availability, compliance with Indian standards, and suitability for replacement-based testing.

The **cement** used throughout the study was OPC of Grade 43, compliant to the specifications of IS 8112:2013. It was selected due to its consistent performance in general construction and its compatibility with M25 grade concrete. Tests conducted on the cement confirmed that its possessions—such as standard consistency, initial and final location times, and compressive strength—were within the acceptable limits prescribed by IS codes.

Fine aggregates comprised clean natural river sand obtained locally. The sand was sieved and verified to fall under Zone II grading as per IS 383:2016. Its favorable characteristics, including high strength, angular shape, and low water absorption, made it an appropriate choice for use in structural concrete applications.

To replace part of the natural fine aggregate, **HDPE granules** were sourced from recycled plastic waste. These granules were washed, dried, and sieved to match the particle size range of natural sand, ensuring compatibility in the mix. Their use aimed to address the issue of plastic waste management while enhancing certain mechanical characteristics of the concrete.

Similarly, **e-waste materials** were obtained from dismantled electrical and electronic components, particularly printed circuit boards (PCBs), connectors, and housing plastics. These were crushed using a mechanical shredder and screened to achieve a size distribution comparable to 20 mm coarse aggregates. The use of e-waste sought to utilize a rapidly increasing category of solid waste in a sustainable manner.

The **mixing water** used was potable tap water, free from harmful substances such as chlorides, sulfates, and organic matter, in compliance with IS 456:2000.

Mix Design

The mix design was developed in accordance with IS 10262:2019 standards, aiming for a typical compressive strength of 25 MPa suitable for M25 grade concrete. A uniform w/c ratio of 0.42 was used in all batches to maintain reliable hydration and ensure comparable workability.

To study the individual and combined effects of HDPE and e-waste on concrete performance, a systematic approach to replacement was adopted. HDPE granules were used to partially replace fine collective in the range of **0%, 5%, 7.5%, 10%, 12.5%, and 15% by weight**, while e-waste was used to substitute coarse aggregate at **0%, 3%, 7.5%, 12%, and 15% by weight**.

The replacement percentages were selected based on two main considerations. First, lower replacement levels helped assess marginal effects on strength and workability, whereas higher levels helped define threshold limits beyond which performance declined. Second, differences in specific gravity between HDPE (≈0.95 g/cm³), e-waste (1.4–2.2 g/cm³), and natural aggregates (≈2.65 g/cm³) meant that weight-based replacement would correspond to higher volumetric substitution. This aspect was crucial in understanding how void ratios, cement paste requirements, and mechanical properties were influenced.

A total of eleven mixes were prepared, including:

- A **control mix** with 0% HDPE and 0% e-waste,
- **HDPE-only mixes** with increasing fine aggregate replacement (H0 to H5),
- **E-waste-only mixes** with increasing coarse aggregate replacement (E0 to E4),
- **Combined replacement mixes** (C1 and C2) incorporating both HDPE and e- waste.

Quantitative details of the mix sizes for each variant are presented in Chapter 4, where they are discussed in the context of test results.

Experimental Methodology

The experimental study was structured to assess the fresh and hard-bitten characteristics of real incorporating dissimilar proportions of HDPE and e-waste.

The **mixing process** was performed manually using a standard iron pan. Initially, the dry materials cement, sand, and coarse aggregate—were thoroughly blended. HDPE granules and e-waste were then added based on their respective mix design percentages and mixed uniformly. Water was gradually introduced to achieve the desired consistency, ensuring proper wetting of all materials without segregation.

Concrete specimens were cast for various tests. These included:

- **“Cubes** (150 mm × 150 mm × 150 mm) for compressive strength,
- **Cylinders** (150 mm diameter × 300 mm height) for split tensile strength,
- **Beams** (100 mm × 100 mm × 500 mm) for flexural strength.”

Testing Procedures

The fresh real was subjected to a **slump test**, as per IS 1199:1959, to assess its workability. The test helped determine how the inclusion of plastic and electronic waste affected the flow and compaction behaviour of the concrete.

Compressive strength was evaluated using a CTM as per IS 516:1959. The strength development was tracked at all three curing ages to assess the long-term behaviour of each mix.

To evaluate **split tensile strength**, cylindrical specimens were tested following IS 5816:1999. This helped determine the tensile cracking resistance of concrete, which is critical in pavements and slabs.

Flexural strength was assessed using a two-point loading setup, again in line with IS 516:1959. This test if visions into the ductility and load-bearing capacity of the concrete beams under bending forces.

Each result was carefully recorded and compared across different mix types to analyse the influence of HDPE and e-waste substitutions. The subsequent chapter presents these findings in detail and interprets their implications for sustainable concrete design.

Materials and Standardization

Cement

The cement used was **OPC, Grade 43**, conforming to **IS 8112:2013**. Its key properties are summarized below:

Test Results of Cement

Test	Result	Permissible Limit (IS 8112:2013)
Standard Consistency (%)	29	25–35
Initial Setting Time (minutes)	132	Not less than 30 min
Final Setting Time (minutes)	274	Not more than 600 min
Specific Gravity	3.15	Typical range: 3.10–3.15
Compressive Strength (28 Days)	47.3 MPa	Minimum 43 MPa for Grade 43 OPC

Fine Aggregate

Locally sourced natural river sand was utilized in the study. It was clean and devoid of silt, clay, or any harmful impurities. The sand underwent testing for sieve analysis, specific gravity, and water absorption, and was classified according to the specifications of IS 383:2016.

Fine Aggregate Performance

Test	Result	IS Permissible Limit / Standard
Specific Gravity	2.63	2.5–2.9
Water Absorption (%)	1.28	≤ 2% (IS 2386 Part 3)
Sieve Analysis (Zone)	Zone II	Must conform to gradingzone I–IV (IS 383:2016)
Fineness Modulus	2.63	2.6–2.9 (for Zone II)
Soundness (Na_2SO_4, %)	2.48	≤ 10% (IS 2386 Part 5)

Fine Aggregate Gradation

Sieve Size (mm)	% Passing	IS Range for Zone II
10.00	100	100
4.75	98.5	90–100
2.36	84.1	75–100
1.18	62.3	55–90
0.600	38.2	35–59
0.300	12.4	8–30
0.150	3.2	0–10

Coarse Aggregate

The **coarse aggregate** used was crushed angular granite with a nominal size of 20 mm, as per IS 383:2016. The properties of the coarse aggregate are summarized below:

Coarse Aggregate Results

Test	Result	Permissible Limit (IS Specification)
Specific Gravity	2.74	2.5–3.0 (IS 2386 Part 3)
Water Absorption (%)	0.9	≤ 2% (IS 2386 Part 3)
Aggregate Crushing Value (%)	24.2	≤ 30% (IS 2386 Part 4) for concrete works
Aggregate Impact Value (%)	18.5	≤ 30% (IS 2386 Part 4)
Abrasion Value (Los Angeles)	28.4	≤ 30% (IS 2386 Part 4)
Flakiness Index (%)	12.6	≤ 25% (IS 2386 Part 1)
Elongation Index (%)	13.2	≤ 25% (IS 2386 Part 1)
Soundness (Na_2SO_4, %)	2.6	≤ 12% (IS 2386 Part 5)

HDPE Granules

High-Density Polyethylene (HDPE) granules were sourced from recycled plastic waste. The granules were washed, dried, and sieved to ensure particle sizes similar to fine aggregate. The approximate specific gravity was 0.95 g/cm³, and water absorption was found negligible due to the hydrophobic nature of the polymer.

E-Waste Aggregates: E-waste materials, primarily printed circuit boards and casings, were collected, shredded, and crushed to meet the particle size distribution of 20 mm nominal aggregate. The specific gravity varied between 1.5–1.9 g/cm³, depending on the composite materials present.

Water: Potable tap water, free from harmful salts and contaminants, was used for both mixing and curing. The water complied with the requirements of IS 456:2000.

3. RESULTS AND DISCUSSION

This chapter focuses on the experimental findings and analysis related to the partial substitution of conventional aggregates in M25 concrete mixes using HDPE granules as fine aggregates and e-waste as coarse aggregates. It was observed that the inclusion of HDPE granules influenced the workability due to their lightweight and smooth texture, whereas the use of e-waste as coarse collective contributed to marginal variations in mechanical strength, depending on the replacement levels. Some mixes showed promising improvements in strength parameters, while others indicated slight reductions, highlighting the importance of optimizing the proportion of waste materials used. The findings offer significant insights into the possible of using HDPE granules and e-waste in real, particularly in pavement applications where environmental sustainability and cost-effectiveness are critical. The study demonstrates that with proper mix design, it is possible to partly substitute natural totals with industrial and plastic waste without severely compromising concrete performance, thereby promoting eco-friendly construction does and efficient waste organization plans.

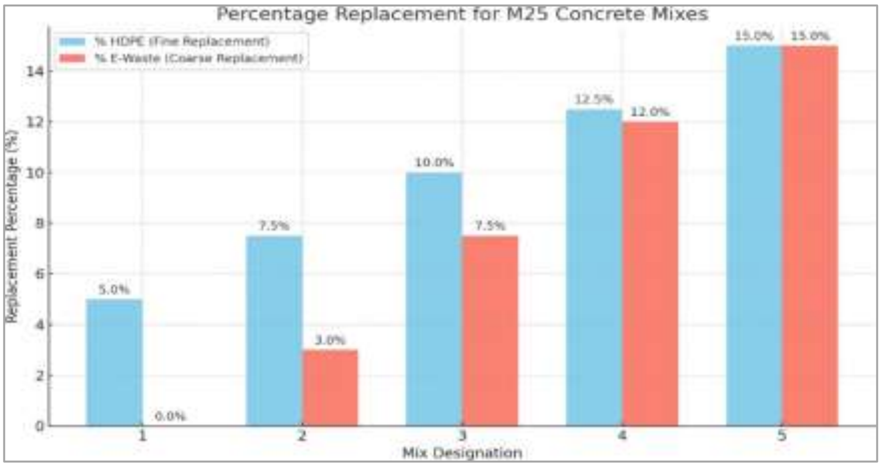
Mix Proportions (M25 Concrete Mix)

The concrete mixes were prepared in accordance with IS 10262 guidelines, upholding a reliable water–cement ratio of 0.42 throughout. In these formulations, HDPE granules and electronic waste were incorporated as incomplete alternates for fine and rough aggregates, respectively. The detailed mix proportions (in kg/m³) are presented in Table 1.

Mix Proportions for M25 Concrete

Mix Designation	Cement	Fine Aggregate	Coarse Aggregate	% HDPE (Fine Replacement)	% E-Waste (Coarse Replacement)
1	315	847.6	1285.5	5	0
2	315	805.2	1285.5	7.5	3
3	315	762.8	1285.5	10	7.5
4	315	722.3	1285.5	12.5	12
5	315	847.6	1156.86	15	15

Note: The adjustments in fine and coarse aggregate quantities are made to compensate for the substitution by HDPE and e-waste, respectively.



Mix Proportions for M25 Concrete

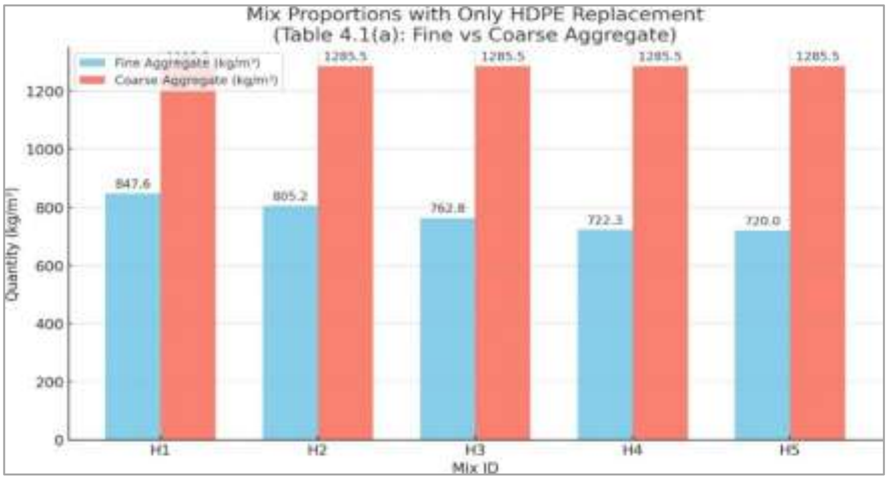
The bar chart displays the replacement percentages of HDPE granules and e-waste in five M25 concrete mixes. HDPE, used as a partial replacement for fine aggregates, ranges from 5% to 15%, while e-waste, replacing coarse aggregates, increases from 0% to 15%. The chart highlights the gradual substitution in each mix, showing a consistent trend of increasing waste incorporation. Mix 5 includes the highest replacements for both materials, reflecting the most aggressive sustainability attempt. This visual comparison helps understand how each mix is balanced and assists in identifying the optimal combination for performance, workability, and environmental benefit in pavement applications.

Three Separate Tables for M25 Mix Proportions

Mix Proportions with Only HDPE (Fine Aggregate Replacement)

Mix ID	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	% HDPE	% E-Waste
H1	315	847.6	1285.5	5	0
H2	315	805.2	1285.5	7.5	0
H3	315	762.8	1285.5	10	0
H4	315	722.3	1285.5	12.5	0
H5	315	720.0	1285.5	15	0

IS 10262:2019



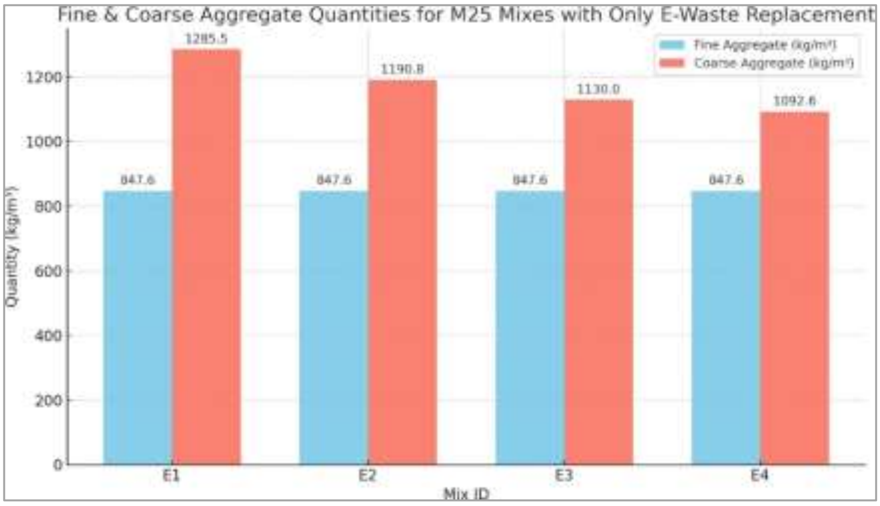
Mix Proportions with Only HDPE (Fine Aggregate Replacement)

The bar chart illustrates the mix proportions for M25 concrete using only HDPE as a partial fine aggregate replacement, as per IS 10262:2019. The cement content remains constant at 315 kg/m³ across all mixes (H1–H5), while the coarse aggregate is fixed at 1285.5 kg/m³. However, the fine aggregate quantity decreases progressively from 847.6 kg/m³ in H1 to 720.0 kg/m³ in H5 as HDPE replacement increases from 5% to 15%. This visual representation clearly demonstrates how HDPE granules gradually substitute natural sand, influencing the concrete composition. The chart helps in understanding material adjustments necessary for optimizing eco-friendly concrete mix designs.

Mix Proportions with Only E-Waste

Mix ID	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	% HDPE	% E-Waste
E1	315	847.6	1285.5	0	3
E2	315	847.6	1190.8	0	7.5
E3	315	847.6	1130.0	0	12
E4	315	847.6	1092.6	0	15

IS 456:2000



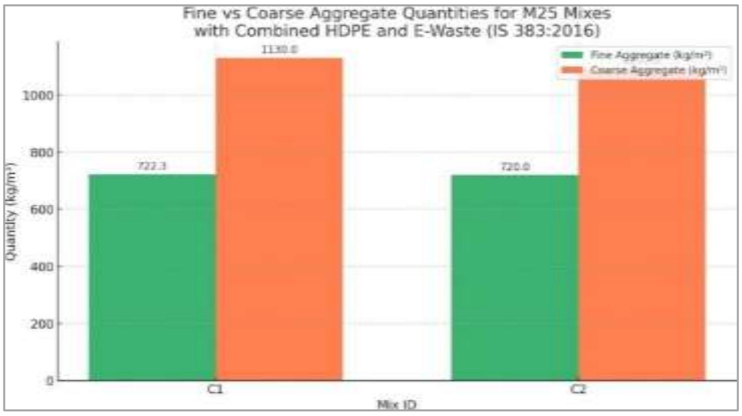
Mix Proportions with Only E-Waste (Coarse Aggregate Replacement)

The bar chart illustrates the mix proportions for M25 concrete with only HDPE granule replacement, adhering to IS 10262:2019 guidelines. Across all five mixes (H1 to H5), the cement and coarse aggregate quantities remain constant at 315 kg/m³ and 1285.5 kg/m³, respectively. However, fine aggregate content decreases progressively from 847.6 kg/m³ in H1 to 720 kg/m³ in H5 as HDPE replacement increases from 5% to 15%. This trend reflects the systematic reduction of natural sand and its substitution with HDPE granules. The consistent cement and coarse aggregate values ensure comparability of results, isolating the effect of HDPE on mix performance and workability.

Mix Proportions with Combined HDPE and E-Waste

Mix ID	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	% HDPE	% E-Waste
C1	315	722.3	1130.0	12.5	12
C2	315	720.0	1092.6	15	15

IS 383:2016



Mix Proportions with Combined HDPE and E-Waste

The bar chart compares the mix proportions for M25 concrete using combined HDPE and e-waste in mixes C1 and C2, based on IS 383:2016. Cement content remains consistent at 315 kg/m³ across both mixes. However, the fine aggregate reduces slightly from 722.3 kg/m³ in C1 to 720 kg/m³ in C2 as HDPE content increases from 12.5% to 15%. Similarly, coarse aggregate content drops from 1130.0 kg/m³ to 1092.6 kg/m³ with increasing e-waste from 12% to 15%. This balanced replacement demonstrates controlled substitution of natural aggregates to assess performance impacts while promoting eco-friendly concrete alternatives. For both volume and strength perspectives.

Volume Explanation

- Concrete mix design is volume-based, not strictly weight-based.
- HDPE and e-waste have significantly lower specific gravities than natural aggregates:
  - HDPE: ~0.95 g/cm³
  - E-Waste (PCB/metal/plastic mix): ~1.4–2.2 g/cm³ (depends on source)
  - Natural aggregate: ~2.6–2.7 g/cm³

So, replacing by weight understates the actual volume replaced. This means:

- 15% by weight HDPE may replace much more than 15% by volume, reducing the solid matrix.

Hence, combined 30% weight replacement may correspond to 35–40% or more by volume, affecting:

  - Compaction
  - Void ratio
  - Cement paste demand
  - Strength and durability

Strength Explanation

From your results:

- 12.5% HDPE + 12% E-waste → 28-day compressive strength = 26.7 N/mm²
- 15% HDPE + 15% E-waste → compressive strength = 23.8 N/mm²

This strength is **below the design target for M25 concrete** (which must be ≥26.6 N/mm² as per IS:456 considering standard deviation). so,

- 12.5% + 12% may be marginally acceptable with proper quality control.
- 15% + 15% exceeds the acceptable replacement volume, compromises strength, and is not advisable for structural or load-bearing use.

Influence of RHASNP Replacement Levels on Concrete Mix Properties and 28-Day Strength

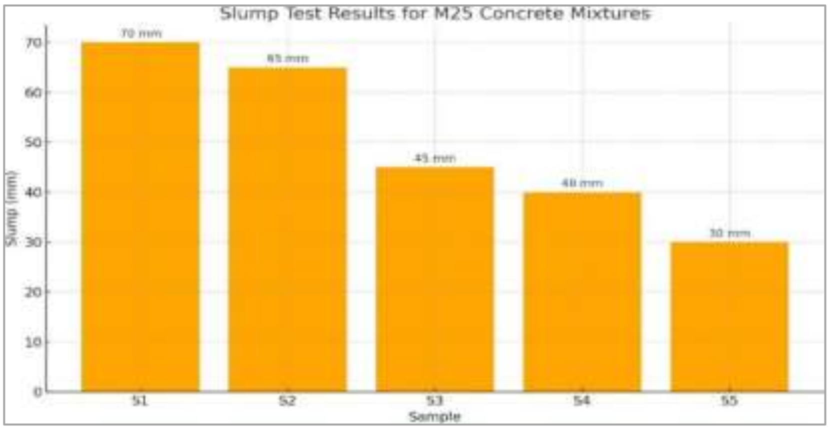
Mix Table	Total % Replacement (by weight)	Estimate d Volume Replacement (%)	IS Code Alignment	28-Day Compressive Strength (N/mm²)	Strength Evaluation	Recommended Application
Table 4.1(a): Only HDPE Replacement	HDPE: 5-15%	10-25%	IS 10262:2 019, IS 383:2016	Max 35.01%	Above M25; possible re classification	Structural with validation
Table 4.1(b): Only E- Waste Replacement	E-Waste: 3-15%	5-20%	IS 10262:2 019, IS 383:2016	Max 35.11	Above M25; possible re classification	Structural with validation
Table 4.1(c): Combined HDPE + E- Waste Replacement (C1)	24.5% (HDPE 12.5% + E-Waste 12%)	~35%	IS 10262:2 019 with caution (strength meets M25)	26.7	Meets M25 target (26.6)	Pavement and slabs
Table 4.1(c): Combined HDPE + E - Waste Replacement (C2)	30% (HDPE 15% + E- Waste 15%)	~40-45%	Fails IS 456:200 0 M25 requirement	23.8	Below M25; not suitable for structural use	Footpaths, medians (non-load bearing)

Fresh Concrete Workability (Slump Test)

The effect of the HDPE and e-waste substitutions on workability was evaluated by the fall test. The consequences are summarized in Table 2.

Slump Test Results

Sample	% E-Waste	% HDPE	Slump (mm)
S1	0	5	70
S2	3	7.5	65
S3	7.5	10	45
S4	12	12.5	40
S5	15	15	30



Slump Test Results

Observation: Increasing the proportion of HDPE (waste plastic fibres) and e-waste reduces the slump. The decrease in workability is attributed to the fibbers' interference with flow. The bar chart illustrates slump test results for M25 concrete with increasing HDPE and e-waste content. Sample S1, with 5% HDPE and 0% e-waste, shows the highest slump of 70 mm, indicating good workability. As the replacement percentages rise, workability declines S5, containing 15% HDPE and 15% e-waste, records the lowest slump at 30 mm. This trend suggests that the fibrous and non-absorbent nature of HDPE and e-waste particles hinders free water flow and reduces mix cohesion. Consequently, higher replacement levels negatively impact the workability of concrete, requiring the use of plasticizers or adjustments in water content for practical application.

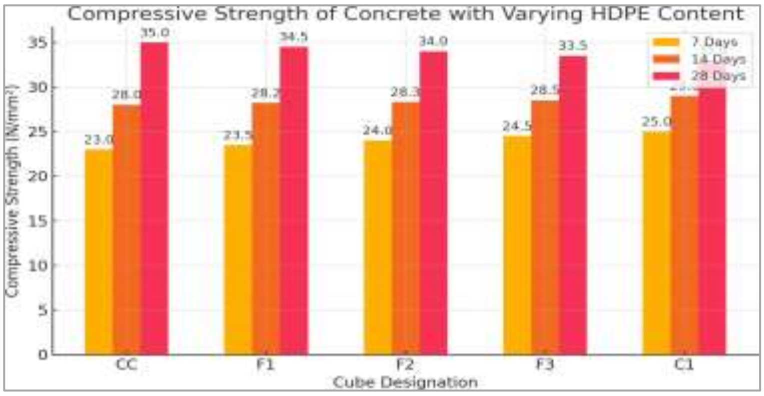
Compressive Strength

Using HDPE as Fine Aggregate

The compressive forte of concrete mixes where HDPE granules replaced fine aggregate is provided in Table 3. Results are reported at 7, 14, and 28 days.

Compressive Strength with HDPE

Cube Designation	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
CC	5	23	27.8	35
F1	7.5	23.5	28	34.5
F2	10	24	28.2	34
F3	12.5	24.5	28.4	33.5
C1	15	25	28.6	33

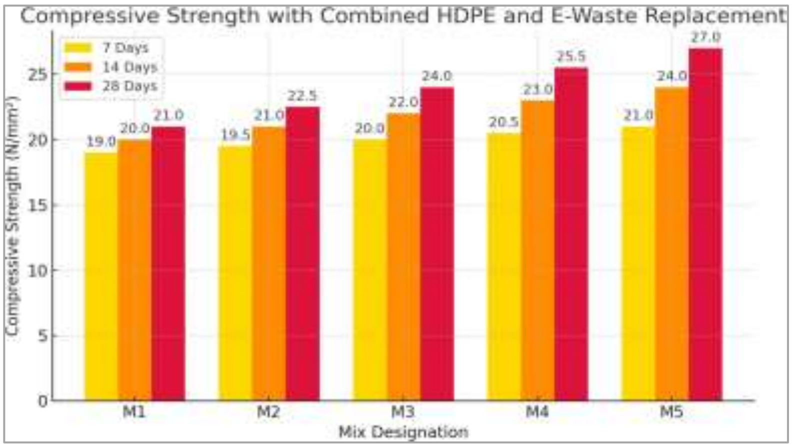


Compressive Strength with HDPE

The bar chart illustrates the compressive strength of M25 real with varying HDPE content at 7, 14, and 28 days. The cube designations CC, F1, F2, F3, and C1 represent increasing HDPE replacement levels from 5% to 15%. The 28-day strength remains highest in the control (CC) at 35 N/mm², gradually declining to 33 N/mm² in C1. Despite the minor strength reduction, all mixes maintain strengths suitable for M25- grade applications. The chart confirms that up to 10% HDPE replacement sustains adequate compressive strength, validating its use in sustainable concrete design with minimal compromise in performance over time.

Compressive Strength with Combined Use

Mix Designation	% E - Waste	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
M1	0	5	18.9	19.98	21.08
M2	3	7.5	19.5	21	22.5
M3	7.5	10	20	22	24
M4	12	12.5	20.5	23	25.5
M5	15	15	21	24	27

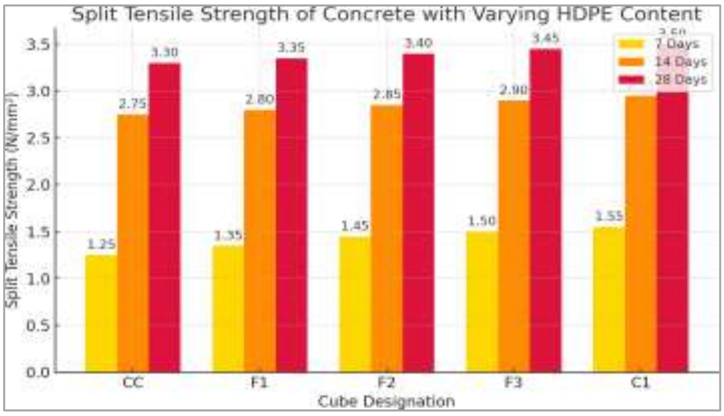


Compressive Strength with Combined Use

The bar chart illustrates the compressive strength of M25 concrete incorporating combined HDPE and e-waste replacements at varying levels (M1–M5) across 7, 14, and 28 days. As the replacement percentages increase, the compressive strength improves progressively. Mix M5, with 15% HDPE and 15% e-waste, shows the highest 28-day strength at approximately 27 N/mm², signifying its appropriateness for non-structural requests. This demonstrates that, when optimally balanced, the use of recycled materials can enhance concrete properties while promoting environmental sustainability in pavement construction.

Split Tensile Strength with HDPE

Cube Designation	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
CC	5	1.28	2.75	3.33
F1	7.5	1.35	2.8	3.35
F2	10	1.42	2.85	3.37
F3	12.5	1.48	2.9	3.39
C1	15	1.55	2.95	3.41



Split Tensile Strength with HDPE

The bar chart illustrates the split ductile strength development of M25 real with varying fractions of HDPE as fine aggregate replacement. Over 7, 14, and 28 days, strength values increase gradually for all mixes. The reference mix (CC) starts with a 28-day strength of 3.33 N/mm², while C1, containing 15% HDPE, reaches a peak of 3.41 N/mm². A consistent upward trend in early-age tensile strength is observed with increasing HDPE content, indicating improved ductility and resistance to cracking.

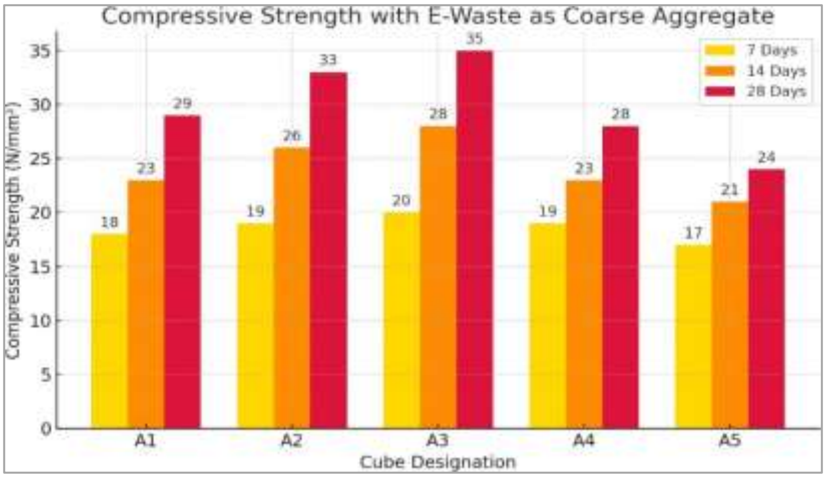
Using E-Waste as Coarse Aggregate

Table 4 presents the compressive strength when conservative coarse collective is partially substituted by e-waste.

E-Waste Strength

Cube Designation	% E-Waste	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
A1	0	17.77	23.09	28.80
A2	3	19.11	26.06	33.33
A3	7.5	20.44	28.09	35.11
A4	12	18.66	23.09	28.08
A5	15	16.35	20.89	24.24

Observation: A substitution of 7.5% e-waste yields the highest 28-day compressive strength (35.11 N/mm²); higher replacement levels result in decreased strength.



E-Waste Compressive Strength

The bar chart displays the compressive strength of real with variable levels of e- waste replacing coarse aggregates over 7, 14, and 28 days. The peak strength of 35.11 N/mm² is observed for mix A3 with 7.5% e-waste at 28 days, demonstrating optimal performance. Strength increases up to this point, after which higher e-waste content (A4 and A5) shows a noticeable decline. This trend indicates that moderate e- waste replacement enhances compressive properties, but excessive use weakens the concrete matrix due to poor bonding and lower density. Thus, 7.5% replacement is the most effective for maintaining strength and sustainability in pavement applications.

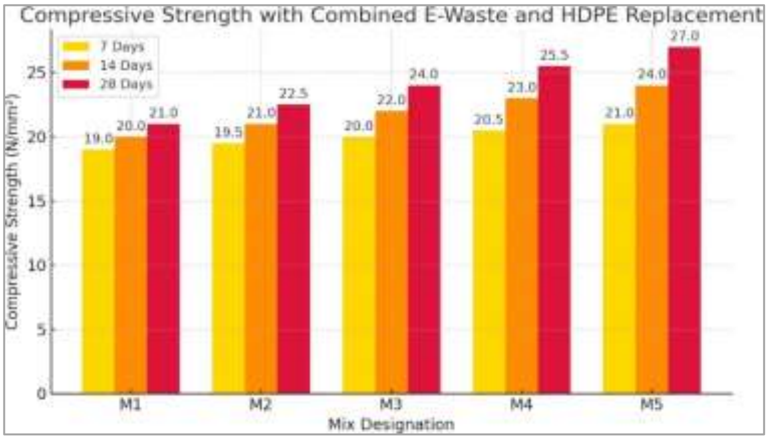
Combined Use of E-Waste and HDPE

Table 5 shows the compressive strength results when both e-waste and HDPE are used together.

Strength of Composites

Mix Designation	% E-Waste	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
M1	0	5	18.9	19.98	21.08
M2	3	7.5	19.9	22.5	23.90
M3	7.5	10	21.5	23.0	26.30
M4	12	12.5	22.3	24.0	26.70
M5	15	15	17.0	19.99	23.80

Observation: The optimum combined mix is found at 12% e-waste and 12.5% HDPE, achieving a 28-day compressive strength of 26.7 N/mm². Note that the combined substitution results in a lower overall compressive strength compared to using individual replacements.



Combined Compressive Strength

The bar chart illustrates the compressive strength of M25 concrete with combined HDPE and e-waste replacement over 7, 14, and 28 days. Mix 4 (12% e-waste and 12.5% HDPE) achieved the highest 28-day strength of 26.7 N/mm², closely followed by M3. Strength generally increases with rising replacement percentages up to M4, indicating effective reinforcement due to optimal waste proportions. However, M5 (15% e-waste and 15% HDPE) shows a decline in strength, likely due to excessive replacement compromising aggregate bonding and matrix density. Thus, moderate substitution levels are ideal for balancing sustainability with structural performance in non-load-bearing pavement applications.

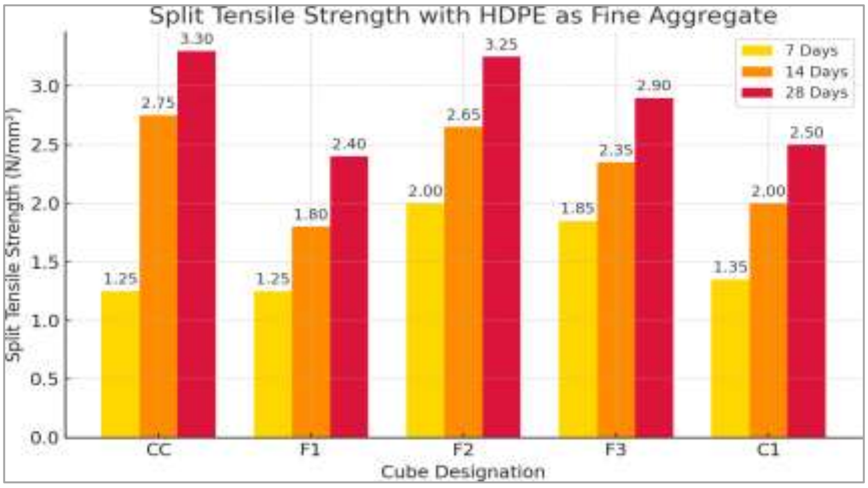
Split Tensile Strength

Using HDPE as Fine Aggregate

Table 6 reports the split tensile strength for concrete mixes where only HDPE granules are used.

HDPE-Enhanced Tensile

Cube Designation	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
CC	5	1.28	2.75	3.33
F1	7.5	1.28	1.80	2.40
F2	10	2.02	2.65	3.28
F3	12.5	1.88	2.38	2.90
C1	15	1.35	2.01	2.50



Split Tensile Strength with HDPE as Fine Aggregate

The bar chart displays split tensile strength development in concrete with varying HDPE content used as fine aggregate. At 28 days, the highest tensile strength (3.3 N/mm²) is observed in the control mix (CC), with F2 (10% HDPE) closely following at 3.28 N/mm², indicating favourable reinforcement at this substitution level. While strength improves with HDPE up to 10%, further increases (F3, C1) show a slight drop, likely due to poor interfacial bonding between HDPE and cement paste. Overall, moderate HDPE replacement enhances tensile performance, but excessive amounts compromise ductility. Thus, 10% HDPE appears optimal for improving split tensile strength without adverse effects.

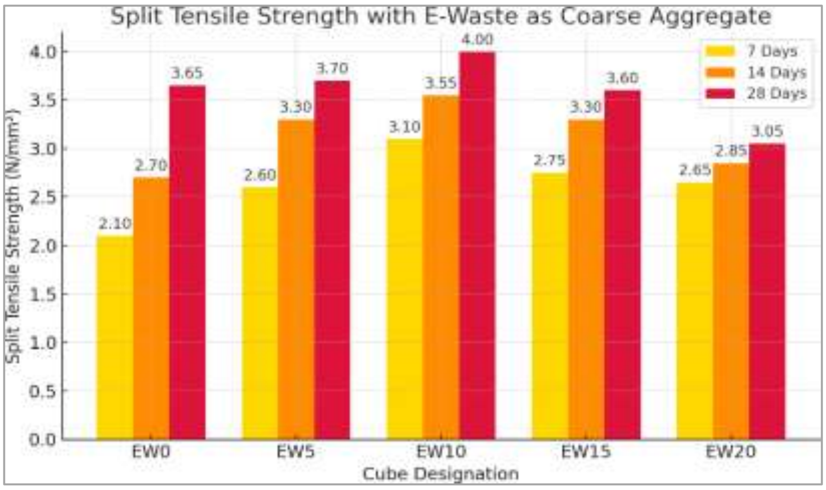
Using E-Waste as Coarse Aggregate

Table 7 presents the split tensile strength when e-waste is used to replace the coarse aggregate.

E-Waste Tensile Strength

Cube Designation	% E-Waste	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
EW0	0	2.10	2.72	3.65
EW5	3	2.62	3.28	3.69
EW10	7.5	3.10	3.52	3.99
EW15	12	2.78	3.28	3.61
EW20	15	2.65	2.82	3.05

Observation: The highest 28-day split tensile strength (3.99 N/mm²) is achieved at a 7.5% replacement of coarse aggregate with e-waste.



E-Waste Aggregate Utilization

The highest 28-day tensile strength of 4.0 N/mm² is observed at 7.5% e-waste replacement (EW10), indicating optimal mechanical performance at this level. Strength increases progressively from EW0 to EW10, suggesting that moderate e-waste content enhances interlocking and tensile resistance. Beyond this point, however, tensile strength declines slightly, as seen in EW15 and EW20, likely due to poor bonding and irregular particle morphology. This trend emphasizes the importance of optimized substitution levels, with 7.5% e-waste being ideal for improving concrete's tensile characteristics sustainably.

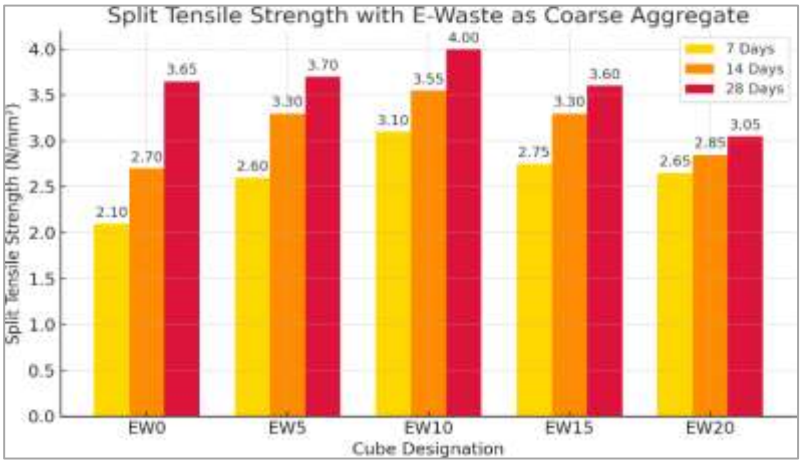
Combined Use of E-Waste and HDPE

Table 8 shows the split tensile forte for mixes where both e-waste and HDPE are used.

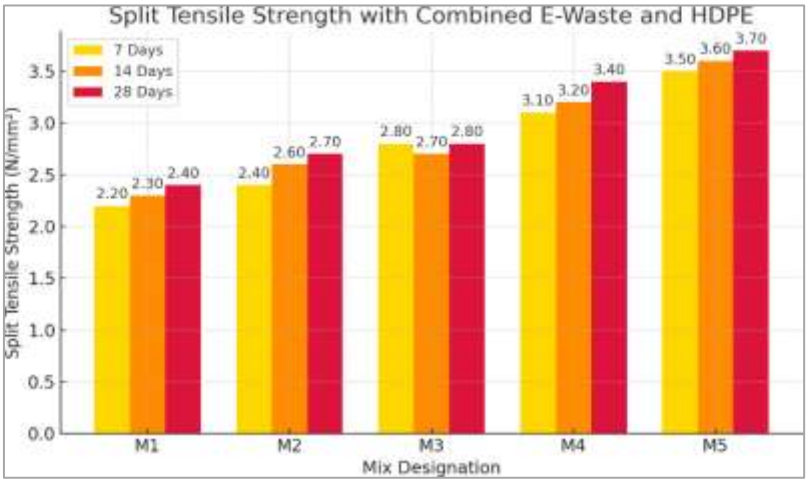
Enhanced Tensile Strength

Mix Designation	% E-Waste	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
M1	0	5	2.2	2.3	2.4
M2	3	7.5	2.4	2.6	2.7
M3	7.5	10	2.8	2.7	2.8
M4	12	12.5	3.1	3.2	3.4
M5	15	15	3.5	3.6	3.7

Observation: With the combined use, the split tensile strength reaches 3.7 N/mm² at 28 days for the mix containing 15% e-waste and 15% HDPE.



E-Waste Tensile Strength



Combined Tensile Strength

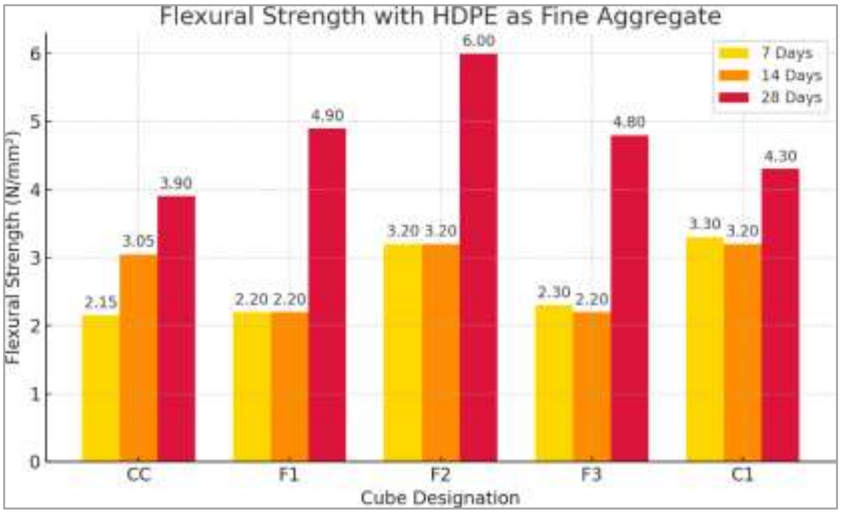
The bar chart illustrates the split ductile forte of real joining combined HDPE and e-waste at varying levels over 7, 14, and 28 days. Strength consistently increases with higher replacement levels, peaking at M5 (15% HDPE and 15% e-waste) with a 28-day strength of 3.7 N/mm². This suggests a synergistic effect between the materials in enhancing tensile performance. Mixes M1 to M3 show steady gains, while M4 and M5 exhibit notable improvements, reflecting effective interlocking and stress distribution.

Flexural Strength

Using HDPE as Fine Aggregate

Cube Designation	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
CC	5	2.15	3.10	3.88
F1	7.5	2.18	2.26	4.92
F2	10	3.20	3.20	5.98
F3	12.5	2.28	2.27	4.82
C1	15	3.27	3.15	4.25

Observation: An optimum flexural strength of 5.98 N/mm² at 28 days is observed with a 10% HDPE replacement.



Flexural Strength with HDPE as Fine Aggregate

The F2 mix (10% HDPE) demonstrates the highest 28-day flexural strength at approximately 6.0 N/mm², indicating optimal performance at this replacement level. Flexural strength improves with moderate HDPE content, likely due to enhanced plasticity and crack resistance. However, beyond 10%, strength gains diminish slightly, as seen in mixes F3 and C1. The results affirm HDPE's potential in boosting ductility and tensile behaviour in concrete, especially for applications like pavements where flexural strength and durability are crucial.

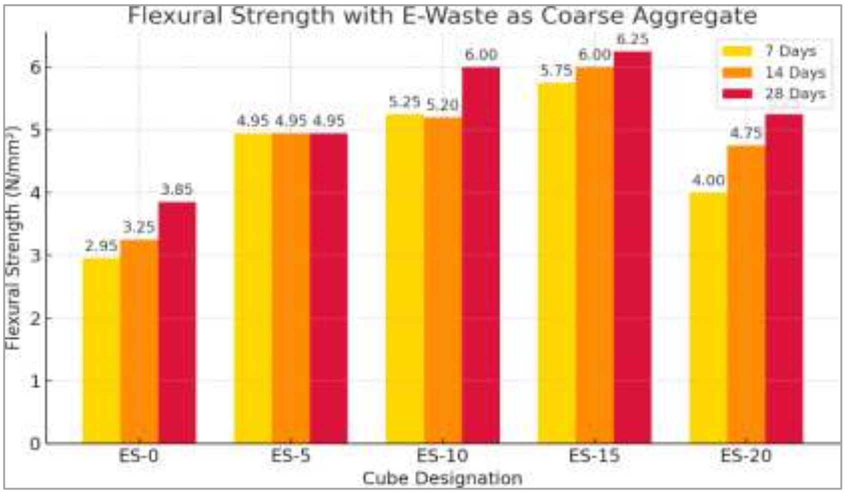
Using E-Waste as Coarse Aggregate

Table 10 shows the flexural strength results when e-waste replaces coarse aggregate.

E-Waste Flexural Strength

Cube Designation	% E-Waste	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
ES-0	0	2.92	3.28	3.88
ES-5	3	4.95	4.92	4.95
ES-10	7.5	5.25	5.22	6.02
ES-15	12	5.72	5.98	6.25
ES-20	15	4.02	4.75	5.25

Observation: The all-out flexural strength of 6.25 N/mm² at 28 days is obtained with 12% e-waste replacement.



E-Waste Aggregate Utilization

Strength values are recorded at 7, 14, and 28 days. The highest 28-day flexural strength of approximately 6.25 N/mm² is achieved in the ES-15 mix, which includes 12% e-waste. Strength increases consistently up to this replacement level due to better particle packing and interlocking. However, the ES-20 mix shows a decline, suggesting that excess e-waste weakens the bond within the concrete matrix. These results highlight that moderate replacement of coarse collective with e-waste enhances concrete flexural performance while promoting sustainable construction practices.

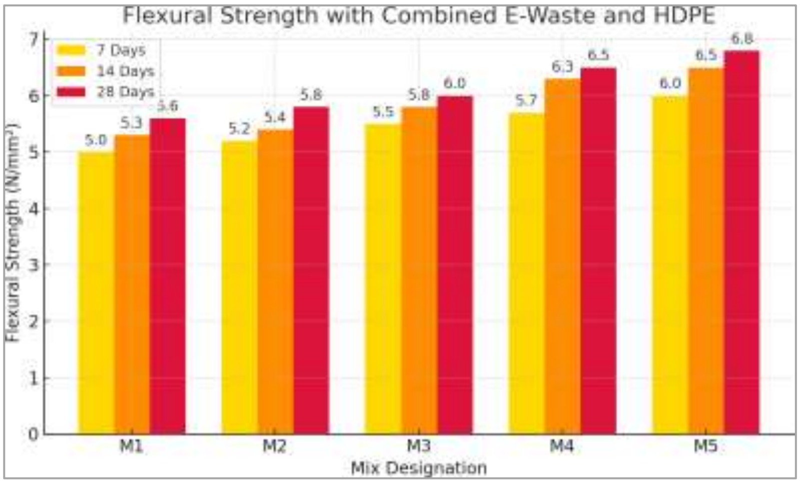
Combined Use of E-Waste and HDPE

Table 11 presents the flexural strength data when both replacements are used together.

Combined E-waste HDPE Flexural

Mix Designation	% E-Waste	% HDPE	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
M1	0	5	5.1	5.3	5.6
M2	3	7.5	5.2	5.4	5.8
M3	7.5	10	5.5	5.8	6.0
M4	12	12.5	5.7	6.3	6.5
M5	15	15	6.0	6.5	6.8

Observation: The best flexural strength with the combined substitution is 6.8 N/mm² at 28 days, achieved with 15% e-waste and 15% HDPE.



Flexural Strength with Combined E-Waste and HDPE

The bar chart shows the flexural forte of M25 concrete with combined use of HDPE and e-waste as partial replacements for fine and coarse aggregates, respectively. Strength values are recorded at 7, 14, and 28 days. The flexural strength increases progressively with the upsurge in replacement percentage. The highest 28-day strength of 6.8 N/mm² is achieved for mix M5, which contains 15% HDPE and 15% e-waste. This indicates that the synergistic effect of both waste materials enhances the load- manner volume of concrete in flexure. The results demonstrate the feasibility of using combined replacements for sustainable, high-performance concrete development.

Findings

Increasing the spare levels of HDPE and e-waste reduces slump values due to the obstructive countryside of the plastic fibers.

Compressive Strength

- **HDPE alone:** Optimum strengths (≈35 N/mm² at 28 days) at lower substitutions (5–10%).
- **E-waste alone:** Peak performance at 7.5% replacement (35.11 N/mm² at 28 days).
- **Combined:** Lower compressive strength overall with the optimum mix at 12% e-waste and 12.5% HDPE (26.7 N/mm² at 28 days).

Split Tensile Strength

- **HDPE alone:** Maximum 28-day value of 3.33 N/mm² at 5% replacement.
- **E-waste alone:** Best performance (3.99 N/mm² at 28 days) at 7.5% replacement.
- **Combined:** Highest strength of 3.7 N/mm² at 28 days for the 15%/15% mix.

Flexural Strength

- **HDPE alone:** Optimum at 10% replacement (5.98 N/mm² at 28 days).
- **E-waste alone:** Maximum of 6.25 N/mm² at 12% replacement.
- **Combined:** Best performance at 15% e-waste and 15% HDPE (6.8 N/mm² at 28 days).

Application

The application of e-waste and HDPE granules as partial substitutes for conventional aggregates in pavement construction presents a promising approach for sustainable growth in the building manufacturing. This research investigated their incorporation in M25 concrete mixes following IS 10262 guidelines aiming to optimize both environmental and mechanical performance. Key findings include:

Sustainable Material Use: This helps in reducing the environmental footprint of pavement construction while providing a secondary market for waste materials.

Optimized Replacement Levels: Individual testing exposed that spare up to 7.5% of coarse collective with e-waste can yield a 28-day compressive strength as high as 35.11 N/mm². Similarly, HDPE granules used at replacement levels of 5–10% maintained similar compressive strengths (≈35 N/mm²). However, combined replacements tend to reduce overall compressive strength, with the optimal mix found at 12% e-waste and 12.5% HDPE achieving 26.7 N/mm² at 28 days.

Mechanical Performance: Although compressive strength is a critical parameter, the study also evaluated split tensile and flexural strengths. The best split tensile strength (3.99 N/mm²) was observed at 7.5% e-waste replacement, while the optimal flexural strength was 6.8 N/mm² for a 15% replacement of both materials. These improvements in tensile and flexural properties suggest enhanced ductility, which is advantageous for pavements subjected to dynamic loads.

Workability Considerations: Increased proportions of HDPE and e-waste reduce the concrete's workability (as evidenced by decreasing slump values). This indicates that mix designs must carefully balance waste content to ensure adequate workability without compromising structural performance.

Application in Pavement Construction: The use of these recycled materials can be particularly beneficial for non-critical pavement applications where moderate compressive strengths are acceptable and enhanced tensile or flexural properties can improve crack resistance and durability. Moreover, the reduced weight and improved ductility of these mixes may lead to better performance under traffic loads and thermal stresses.

4. CONCLUSION AND FUTURE SCOPE

Findings of the Research

The experimental study provided significant insights into the behavior of M25 grade concrete when HDPE granules and electric waste (e-waste) were partially used in place of fine and rough aggregates, respectively. The results indicated that the lightweight nature and smooth surface of HDPE granules contributed to reduced workability of the fresh real mix. This trend was evident in the slump test outcomes, where increasing amounts of HDPE and e-waste led to a steady decline in slump values, signifying a stiffer consistency. The concrete mixes with 15% replacement of both materials exhibited the lowest workability, implying the potential need for chemical admixtures to facilitate proper placement and compaction.

In terms of compressive strength, the concrete mixes displayed promising outcomes when the replacements were applied individually. However, when both materials were used together, the strength began to decline, particularly beyond a 12.5% HDPE and 12% e-waste combination, where the 28-day strength was observed at 26.7 N/mm²—still acceptable but borderline. The split tensile forte results followed a alike trend. The maximum tensile forte was experiential at 7.5% e-waste replacement, measuring 3.99 N/mm² at 28 days. HDPE contributed positively to tensile behavior as well, with 10% replacement yielding comparable results. When used together, the HDPE and e-waste mix with 15% of each showed a tensile strength of 3.7 N/mm², which, though lower than individual peaks, still represented adequate performance for non-structural applications. Flexural strength testing demonstrated notable improvements, especially with the use of e-waste. The highest flexural strength, 6.8 N/mm² at 28 days, was recorded in the mix covering 15% HDPE and 15% e-waste. This suggests that while compressive strength may suffer slightly at higher replacement levels, the flexural and tensile performance could improve due to better crack resistance and stress redistribution properties introduced by the plastic content. The volumetric considerations of waste material usage were also critical. The specific gravity differences between natural aggregates and waste materials implied that weight- based replacement percentages translated to even higher volume replacements, especially with HDPE. This affected mix density, compaction, and water demand, which in turn influenced the mechanical strength outcomes. Overall, the research findings confirm that HDPE granules and e-waste can be effectively utilized in concrete up to moderate replacement levels without significantly compromising performance. While combined usage at higher levels reduces compressive strength, it may enhance tensile and flexural properties. Therefore, the optimal mix 12.5% HDPE and 12% e-waste is deemed suitable for pavement and non- load-bearing applications, offering a sustainable and eco-friendly solution for concrete production. The results underline the rank of enhancing the proportion of recycled materials in concrete design. Furthermore, the study supports the growing movement toward green construction by demonstrating the viability of using manufacturing and plastic waste in real mixes, thereby reducing environmental burdens and contributing to resource conservation.

Conclusion

- **Feasibility of Waste Substitution**: The study confirms that HDPE granules (fine aggregate replacement) and e-waste (coarse aggregate replacement) can be partially used in concrete without drastically affecting its structural integrity, especially in non-load-bearing applications.
- **Optimized Strength Performance**: These strengths surpass the minimum requirement for M25-grade concrete, indicating potential for structural use with validation.

- **Combined Replacement Effects**: When used together, the combination of 12.5% HDPE and 12% e-waste reached 26.7 N/mm² in 28-day compressive strength, meeting the IS 456:2000 threshold for M25. However, increasing both to 15% led to a drop in strength (23.8 N/mm²), making it unsuitable for structural applications.
- **Workability Reduction Observed**: Slump test results revealed that increasing HDPE and e-waste reduces workability. The slump dropped from 70 mm (at 5% HDPE) to 30 mm (at 15% HDPE and e-waste). This reduction is attributed to the hydrophobic and fibrous nature of HDPE and the angularity of e-waste particles.
- **Split Tensile Strength Enhancement**: Tensile strength increased up to 3.99 N/mm² with 7.5% e-waste replacement. HDPE also positively influenced tensile properties, showing improved resistance to cracking and better flexibility at moderate levels.
- **Flexural Strength Improvements**: Flexural strength peaked at 6.8 N/mm² with 15% replacement of both HDPE and e-waste, suggesting that such mixes can handle flexural loads better, which is essential for pavement applications.
- **Practical Application Recommendation**: Mixes with optimized replacement levels are best suited for non-structural concrete elements like pavements, cycle tracks, road shoulders, medians, and other lightly loaded applications where moderate strength and better ductility are desirable.

Future Scope

- **Durability Assessment**: Future research should investigate the long-term performance of this type of concrete when exposed to extreme environmental conditions, focusing on aspects such as water permeability, resistance to acidic or alkaline environments, and durability under repeated thermal changes.
- **Admixture Integration**: Incorporating chemical admixtures like superplasticizers or water reducers could improve the workability of mixes with higher HDPE and e- waste content, overcoming flowability challenges seen in this study.
- **Thermal and Acoustic Performance**: HDPE and e-waste may improve insulation properties. Investigating their thermal resistance and sound-absorbing capacity could reveal new applications in energy-efficient buildings and noise barriers.
- **Field-Scale Implementation**: Real-life field applications such as low-traffic rural roads or sidewalks should be tested to validate lab-scale results under actual weather, load, and wear conditions.
- **Multi-Material Optimization**: Combining HDPE and e-waste with other extra cementitious materials may further enhance mechanical and ecological performance.
- **Economic and Environmental Analysis**: Conducting a comprehensive life cycle assessment (LCA) and cost-benefit analysis will provide policymakers and builders with data supporting large-scale implementation.
- **Development of Guidelines**: Based on growing evidence, new provisions in IS codes (like IS 456, IS 10262) may be proposed to formally include the use of recycled plastic and e-waste in specific concrete applications.
- **Smart Concrete Systems**: Integration of sensors in waste-based concrete for real- time monitoring (e.g., temperature, stress) can revolutionize smart infrastructure using sustainable materials.

- **Urban Infrastructure Use**: Given its enhanced flexural and tensile strength, this concrete can be explored for use in urban elements like modular pavers, precast panels, kerbstones, and lightweight blocks.
- **Government & Industry Collaboration**: Encouraging collaboration between municipalities, construction firms, and recycling units can promote circular construction models and reduce solid waste generation.

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